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An advanced analytical model for simulating thunderstorm outflows

Andi Xhelaj [a], Massimiliano Burlando [a], Giovanni Solari [a]

[a] *Department of Civil, Chemical and Environmental Engineering*
Polytechnic School, University of Genoa, Via Montallegro 1, Genoa, Italy

ABSTRACT: A diverging wind system known as "downburst" is defined as a strong downdraft which induces an outburst of damaging winds on or near the ground. Severe wind damage in many parts of the world are often due to thunderstorm outflows and they therefore have a focal role in structural safety and design wind speed evaluation. Despite this, there is not yet a shared model for thunderstorm outflows and their action on structures. In this paper, an analytical model that simulates the horizontal mean wind velocity originated from a travelling downburst is proposed. The horizontal wind velocity is expressed as the vector summation of the stationary radial speed generated by an impinging jet, the downdraft translating velocity and the background wind velocity, where the thunderstorm is immersed. All parameters employed in the model are related to meteorological variables that are susceptible of statistical assessment. A parametric study is also developed and coupled with the analytical model in order to investigate several observed downburst events. The different parameters of the downburst such as downdraft diameter, touchdown position, translating downdraft speed and direction, intensity and decay period are estimated through the parametric study in order to reconstruct the space-time evolution of this event.

KEYWORDS: Thunderstorm, analytical model, stationary downburst, translating downburst, synoptic winds, parametric study.

1 INTRODUCTION

The study of thunderstorms and their actions and effects on structures is a dominant topic of the research in wind engineering over the last forty years [1]. Thunderstorms are non-stationary phenomena at the mesoscale, which occur in convective conditions with velocity profiles substantially different from those that are typical of the Planetary Boundary Layer. Design wind velocities with mean return periods greater than 10-20 years are often associated with such phenomena [2]. Despite this reality, there is not yet a shared model for thunderstorm outflows and their action on structures. In this paper, an analytical model that simulates the horizontal mean wind velocity at a fixed height above the ground, originating from a travelling downburst, is proposed. The combined wind velocity experienced at a point as a downburst passes, is assumed to be the vector summation of the radial impinging jet velocity, a translation velocity and a background wind velocity. All parameters employed in the model are related to meteorological variables and are susceptible of statistical assessment. A parametric study is also developed and coupled with the analytical model in order to investigate several observed downburst events. This is achieved by means of an optimization procedure which allows to determine the parameters of the model and hence to reconstruct the space-time evolution of downbursts.

2 DESCRIPTION OF THE MODEL OF DOWNBURST

The model assumes that the resulting horizontal mean wind vector, evaluated at some fixed height above the ground (e.g. 10 m), may be obtained as the vector summation of the radial jet velocity generated by the stationary downburst, the translating velocity of the storm cell and the background synoptic wind velocity, in which the thunderstorm is embedded. Figure 1 shows a schematic view of the model proposed in this paper.

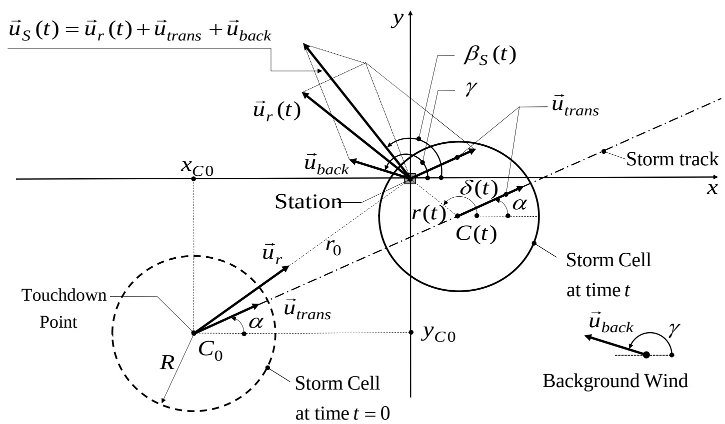

Figure 1 Schematic view of the downburst model

The storm touchdown point (i.e., its center at t = 0) is assumed to be defined by the coordinates, (x_{C0}, y_{C0}), relative to a Cartesian coordinate system, whose origin is identified with an ideal station (i.e. anemometer or point like-structure). In this paper, the radial jet velocity u_r is described in agreement with the Holmes and Oliver (2000) model [3]. In order for the model to represent the full life of the downburst, two intensity functions to account for the time dependency of the storm strength are applied. In literature, until today, the translational component of the thunderstorm cell is often identified with the background wind that may be caused by the local atmospheric circulation, or due to a background synoptic flow. This assumption is based on the hypothesis that the cumulonimbus cloud, within which the downdraft takes place, is carried along its path by a background wind [4]. This hypothesis constitutes a fact that today appears anything but obvious, so that this work presents a clear distinction between the translational velocity of the storm cell and the background wind velocity. The storm is assumed to move in a straight line at a constant translation speed, u_{trans}. The angle, α, which defines the direction of the translating storm (i.e. angle between the *x*-axis and the storm track), is assumed to be constant. Moreover the translating downburst velocity is applied only to a circular area of competence of the downburst, while it is zero outside this area. If u_{back} denotes the module of the background wind velocity which forms and angle γ with the x-axis, then the resultant velocity components at time t, in a Cartesian coordinate system as detected by the station S are given by:

$$\begin{cases} u_{Sx}(t) = u_r(t) \cdot \Pi_r(\mathrm{t}) \cdot \cos(\delta(t)) + u_{trans} \cdot \Pi_{trans}(t) \cdot \cos(\alpha) + u_{back} \cdot \cos(\gamma) \\ u_{Sy}(t) = u_r(t) \cdot \Pi_r(\mathrm{t}) \cdot \sin(\delta(t)) + u_{trans} \cdot \Pi_{trans}(t) \cdot \sin(\alpha) + u_{back} \cdot \sin(\gamma) \end{cases} \tag{1}$$

where δ(t) = instantaneous radial direction from the storm center to the observing point S(0,0); $\Pi_r(t)$ = intensity function applied to the radial jet velocity in agreement with [5]; $\Pi_{trans}(t)$ = intensity function applied to the translating velocity of the storm cell.
Table 1 summarizes the complete parameter list on which the analytical model depends.

Table 1. Model parameters

1 - Maximum radial velocity	$u_{r,max}$
2 - Radius of the downburst	R
3 - Radius of maximum outflow	R_{max}
4 - Period of linear intensification (Π_r)	T_1
5 - Exponential decay constant (Π_r)	c
6 - Touchdown location (at t = 0)	(x_{C0}, y_{C0})
7 - Storm translation speed	u_{trans}
8 - Storm translation direction	α
9 - Background wind speed	u_{back}
10-Background wind direction	γ

3 PARAMETRIC STUDY

A parametric study has been undertaken on the parameters of the analytical model. The purpose of the parametric study is the creation of a wide set of events to compare with observations in order to get the actual downburst's dimensions and relevant kinematic parameters of specific test cases according to a minimization function between simulation and measurements. Multiple field recorded events have been collected throughout two EU projects, "Wind and Ports" (WP) [6] and "Wind, Ports and Sea" (WPS) [7] which have been carried out by the department of Civil, Chemical and Environmental Engineering of the University of Genoa. The recorded thunderstorm events considered in this study were measured by ultrasonic anemometers having a sampling rate of 10 Hz. As the turbulent fluctuation was not included in this work, it is filtered out from the recorded wind velocity. According to Solari et al. [8], the instantaneous wind velocity is decomposed by a moving average filter with an averaging period T = 30 s. The downburst wind velocity varies with the different downburst parameters (see Table 1). Each parameter varies over a range defined according to observations and has a significant influence on the simulation of thunderstorm outflows. The parameters that will be investigated during the parametric study in progress are ($u_{r,max}$, R, T_1, c, x_{C0}, y_{C0}, u_{trans}, α, u_{back}, γ). The object of the study is to estimate the most appropriate value for these parameters, which corresponds to minimize the total square error $\varepsilon_{tot}{}^2 = \sum_{t=0}^{T_{tot}} E_t$ in respect to recorded data, where T_{tot} is the total simulation time and E_t is the summation of the two square errors of wind speed and direction. A further development that will be proposed in the full paper concerns the application of the Buckingham's Π Theorem in order to reduce the number of the ten parameters involved in this procedure. Buckingham's theorem states that the parameters can always be combined to form exactly (10 – r) independent non-dimensional parameters, where r is the rank of the dimensional matrix. Essentially Π Theorem considerably reduces the dimension of the parameter space to explore, leading to a very efficient technique that allows to determine the parameters involved in in parametric study.

4 RESULTS AND DISCUSSION

The coupled parametric-analytical study has confirmed the ability of the analytical model to match the time series of observed wind speeds and directions for the investigated events. For example, Figure 1 shows a downburst that took place in Genoa on 30 September 2012.

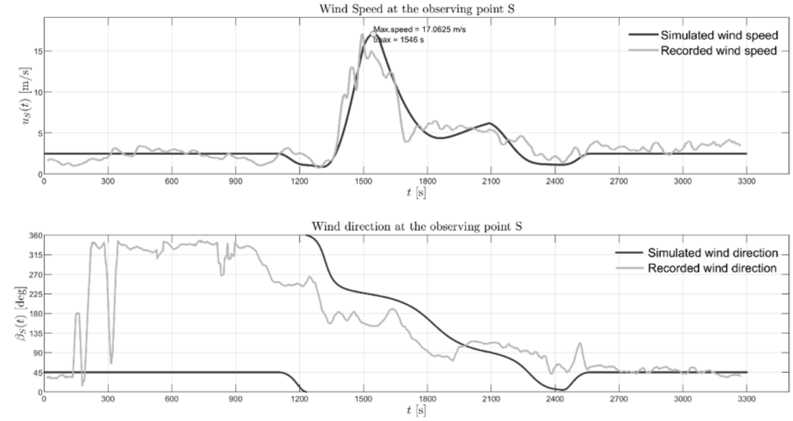

Figure 2 Comparison between simulated and recorded wind speed and direction for the Genoa downburst, 30 September 2012.

The wind speed simulated match the observed data to a very good extent. The wind direction is not properly simulated in the very first part of the signal, but it follows very well the trend and variation of the recorded wind direction. The model parameters and the full reconstruction of this event will be included in the full paper together with other examples.

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